State-of-the-art Superconducting Quantum Interference Devices -SQUIDs- for electrical and magnetic measurements at low and very low temperatures

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National Metrology Institute of Germany

1500 staff members (400 in Berlin)
Motivation

Yesterday: talk by Frank Hekking about the physics of Josephson junctions and dc SQUIDs

Introducing Superconducting Quantum Interference Devices (SQUIDs) as a tool for sensitive electrical and magnetic measurements.

Description of SQUID devices presently (commercially) available. Talk will concentrate on low critical temperature superconductor (LTS) dc SQUIDs.
Outline

- SQUID basics
- SQUID current sensor basics
- State-of-the-art SQUID current sensors
- Application examples
- Handling of SQUIDs
- Auxiliary components
What is a SQUID?

- Most sensitive detector of magnetic flux (changes)

- SQUIDs are very versatile and can be used for sensitive magnetic and electrical measurements

- Operating at cryogenic temperature (77 K down to the mK range)

- SQUID function based on
  - Flux quantization in a superconducting ring
  - Josephson effect

- Low-noise read-out electronics usually operating at room temperature is required
Physicist: "A dc SQUID is a superconducting ring interrupted by two Josephson junctions ..."

Electronics engineer: "A dc SQUID is a low-noise, nonlinear flux-to-voltage converter"
How does a dc SQUID work?
How does a dc SQUID work?

I-V and V-Φ characteristics

$I_0$ – Critical current of the JJ
$\Delta V$ – Voltage swing
$W$ – Working point

Transfer function

$V_\Phi = \delta V/\delta \Phi$

should be maximum
How does a dc SQUID work?

Small-signal SQUID readout

Small change in applied flux $\delta \Phi$ results in small change in SQUID voltage $\delta V$

Main problems:

- Very small voltage across the SQUID: $\Delta V \approx 10...50 \, \mu V$
- Transfer coefficient $V_\Phi = \delta V / \delta \Phi$ depends on SQUID working point
- Very small linear flux range: $\Phi_{lin} << \Phi_0$

Example: Magnetometer with $1 \, \text{nT}/\Phi_0 \rightarrow$ Human heart signal $\approx 0.05 \, \Phi_0$

Main tasks of a SQUID electronics:

- Amplifies the weak SQUID voltage without adding noise
- Linearizes transfer function to provide sufficient dynamic range
How does a dc SQUID work?

Flux Locked Loop (FLL) with direct SQUID read-out

FLL linearizes the V-Φ characteristics and enables a high dynamic range (100 $\Phi_0$)

$V \propto \Phi$

Low-noise preamplifier required
Noise and energy resolution

Thermally induced white noise

Power spectral density of flux noise: \( S_\Phi \approx \frac{S_V}{V_\Phi^2} \)

with \( S_V(f) \) power spectral density of voltage noise

\[ S_\Phi \approx 16k_B T L^2 / R \quad \text{(keep } L \text{ low)} \]

Noise energy:

\[ \epsilon = \frac{S_\Phi}{2L} \]

1/f noise

sources: moving flux vortices, critical current fluctuations in the junctions (HTS SQUIDs)

See e.g. Clarke, „SQUID fundamentals“ in SQUID Sensors, Fundamentals, Fabrication and Applications, NATO ASI vol.329 (1996)
Noise and energy resolution

Flux noise of a PTB SQUID current sensor

- $S^\frac{1}{2} / \Phi_0 / \text{Hz}^{\frac{1}{2}}$
- $f / \text{Hz}$
- $T = 4.2 \text{ K}$
Noise and energy resolution

Example (John Clarke)

L = 200 pH, R = 6 Ω, T = 4.2 K

Spectral flux noise density: \( \sqrt{S_\Phi} \approx 1.2 \, \mu\Phi_0/\sqrt{\text{Hz}} \)

Noise energy: \( \varepsilon \approx 1.5 \times 10^{-32} \, \text{J/Hz} \approx 150 \, \hbar \)

1 \times 10^{-32} \, \text{J} \approx 10^{-13} \, \text{eV} \) is the energy to raise 1 electron through 1 mm in the earth's gravitational field, or \( 10^{-14} \times \) the ground state energy of one hydrogen atom (John Clarke)
How to make a SQUID?
First SQUIDs were made of bulk material

Resistive SQUID for noise thermometry (PTB) with Nb point contact

LTS SQUID Fabrication

3” Si wafer with 183 SQUIDs

Magnetometers fabricated using a Nb/AlO_x/Nb thin-film technology
LTS SQUID Fabrication

Layers

- Si/SiO₂-substrate
- Nb-base electrode
- Nb₂O₅-insulation
- SiₓNᵧ-film
- Au/Pd-resistive layer
- Al₂O₃-barrier
- Nb-counter electrode

Josephson junction
shunt resistor
transformer coils
Example of a LTS SQUID magnetometer

To measure $B$, a fairly large sensing area is needed, because $\Phi = \int B \, dA$

Multiloop SQUID magnetometer

$L = 400 \text{ pH}$

Noise at $T = 4.2 \text{ K}$

$\sqrt{S_\Phi} = 2.6 \, \mu \Phi_0/\sqrt{\text{Hz}} @ 1\text{kHz}$

$\sqrt{S_B} = 1.2 \, \text{fT}/\sqrt{\text{Hz}} @ 1 \text{kHz}$

Drung type design
Chip-size: $7.2 \text{ mm} \times 7.2 \text{ mm}$
Heavily magnetically shielded rooms

Fetal MCG
For a large number of experiments we do not need magnetometers, but sensitive SQUID current sensors.
How to make a SQUID current sensors?

\[ T \leq 5 \text{ K} \]
Application example of SQUID current sensor

Magnetometer consisting of
wire wound pickup coil
and SQUID current sensor

\[ T \leq 5 \text{ K} \]
Magnetometer made of SQUID current sensor
Simple SQUID current sensor

$\sqrt{S_I} \leq 1 \, \text{pA/Hz}^{1/2}$,

$\varepsilon_c \leq 400 \, \text{h}$

$B/\Phi \approx 10 \, \text{nT}/\Phi_0$

$T_{OP}: 4.2\, \text{K}$
Simple SQUID current sensors

Drawbacks

• extremely sensitive to magnetic interferences
• careful magnetic shielding required
• extremely sensitive to vibrations
• limited flexibility regarding input inductance
• operational temperature 1 K – 5 K

Not well suited for many applications, in particular for those in novel cryogen-free cryostats

with mechanical precooling.
What SQUIDs are required?

Extremely **sensitive, robust and easy to handle SQUID current sensors** required for (quantum) measurements at low and ultra-low temperatures

- low input inductance (nH) sensors:
  - read-out of cryogenic radiation detectors
  - TES, HEB, single-photon detectors

- high input inductance (µH) sensors:
  - electromagnetic measurements
  - metrology, Cryogenic Current Comparators (CCC)
  - Nondestructive evaluation (NDE)
  - susceptibility
  - NMR, If-NMR
  - novel biomedical diagnostic tools
  - magnetic nanoparticles

Sensitive magnetometers/gradiometers and nano-magnetometers

- noise measurements
- single magnetic moment detection

large polarizing fields (>>1 mT) are used
State-of-the-art SQUID current sensors
Towards robust low-noise SQUID current sensors

**Goal**
- robust against magnetic interferences
  - gradiometric sensor design, small line width
- operation down to ultra-low temperature (ca. 10 mK)
  - appropriate resistance materials and Josephson junctions
- high flexibility
  - variety of sensor designs: single- and double stage SQUIDs, arrays
- high bandwidth and high slew rate
  - appropriate read-out techniques, e.g. OCF (on chip current feedback)
- easy to handle
  - auxiliary components, computer controlled, user-friendly software

**Solution**

→ gradiometric sensor design, small line width
→ appropriate resistance materials and Josephson junctions
Robust low-noise SQUID current sensors

Gradiometric sensor design

Parallel gradiometer: superconducting loop: \( \rightarrow \) trapped flux
Serial gradiometer: \( \rightarrow \) release of trapped flux with bias current

\[ B_0 = \frac{\pi \Phi_0}{4W^2} \]

\( \rightarrow W_{\text{max}} \leq 5\mu m \)
for cooling in Earth field


Expulsion of vortices in the Nb thin-film patterns

magnetic microscopy of Nb stripes cooled down in ambient field
SQUID array

- low input inductance
- high dynamic range
- not sensitive to magnetic interference
- single-SQUID-like behavior

Gradiometer SQUID

- Single-turn input coil
- SQUID loop
- Josephson junctions
- SQUID-to-SQUID connection
- Cooling fins
• 2 independent 16 SQUID-arrays per chip
• operable at mK-temperatures
• no shielding required
• integrated resistors for biasing radiation detectors (e.g. TES) on chip

\[ \sqrt{S_I} < 5 \text{ pA/}\sqrt{\text{Hz @ 0.1 K}} \]
\[ L_{IN} < 3\text{nH} \]
\[ \varepsilon_C < 57\text{h @0.1 K} \]
\[ P_{\text{Diss}} \sim 1\text{nW (per channel)} \]
Technological limitation

Currently Nb/AlOx/Nb thin-film technology with 2.5 µm photolithographic patterning

**Problem:**
for high input inductance 10..100 turn input coil needed

but

with 2.5 µm linewidth only 1 turn possible!

**Solution:**
input flux transformer
Current sensor with single SQUID

- high input inductance
- high sensitivity
- not sensitive to magnetic interference
2-stage SQUID current sensors

- minimum coupled energy sensitivity
- integrated 2stage SQUID current sensor
- not sensitive to magnetic interference
- single-SQUID-like behavior
2-stage SQUID current sensors

- front-end: single-SQUID, read out with SQUID array
- operable at mK-temperatures
- no shielding required
- $V/\Phi$- characteristics like single-SQUID
- different sizes with $L_{IN}$ from 25 nH to 1.8 $\mu$H
- adjustable input current limiter

\[
\sqrt{S_I} < 0.05 \text{ pA/}\sqrt{\text{Hz}} \ @ \ 0.1K
\]
\[
L_{IN} = 1.05 \mu\text{H}
\]
\[
\varepsilon_C < 8 \text{h} \ @ \ 0.1K
\]
\[
P_{\text{Diss}} \sim 2 \text{ nW}
\]
Example for robust and user-friendly FLL electronics: Directly coupled FLL electronics XXF (developed by PTB and Magnicon)

- 670 surface-mount components on $13 \times 4.3 \text{ cm}^2$ FLL board
- Up to three channels in one FLL unit
- Low noise $0.33 \text{ nV/}\sqrt{\text{Hz}}$ and $2.6 \text{ pA/}\sqrt{\text{Hz}}$
- High bandwidth $20 \text{ MHz}$ (FLL) or $50 \text{ MHz}$ (open-loop)
- Built-in current sources for TES readout and two-stage SQUIDs
- Fast $< 1 \mu\text{s}$ external reset
- Flexible and user-friendly $\rightarrow$ fully computer controlled
Novel SQUID current sensors below 1 K

- 4.2 K → <320 mK: white noise **falls**, but 1/f noise **rises**
- For this example: mK noise **higher** than 4.2 K noise above ≈40 Hz
- 1/f noise can become **significant** even in the **kHz range**
- **Currently under investigation** (other supercond. material)
Wide bandwidth SQUID current sensors

Bandwidth limitation due to cable delay in the FLL
1 m → 10 MHz

How to get faster?

SQUID+FLL at low temperature (4.2K)
- Very high FLL bandwidth ≈ 350 MHz
- Very high slew rate ≈ 80 Φ₀/μs
- BUT: Power dissipation ≈ 10 mW

SQUID with on chip current feedback (OCF)
- Semicond amplifier replaced by SQUID array
- very high small signal bandwidth >200 MHz
- large signal bandwidth 16 MHz
- current noise 7.4 pA/√Hz (L_in < 5 nH)
- very high slew rate >50Φ₀/μs
- Power dissipation ≈ 100 nW
Magnetometers and susceptometers

Integrated miniature multiloop SQUIDs

Sensor noise

$< 4 \text{ fT/} \sqrt{\text{Hz}}$ size M (2.8 mm)

$< 10 \text{ fT/} \sqrt{\text{Hz}}$ size S (1.7 mm)

Integrated susceptometers with 30 µm and 60 µm pick-up loop size for characterization of small particles etc.
Large variety of devices available

Sources of SQUID devices:
IPHT Jena, PTB Berlin, VTT Helsinki, Magnicon Hamburg, Supracon Jena
US: Starcryoelectronics, Tristan
How to operate and handle SQUIDs?
Measurements

Characterization of SQUIDs

- SQUID FLL-electronics
- Computer
- Oscilloscope
- RF shielding
- Spectrum analyzer
- LHe can
- ESD chair
Measurements

Characterization of SQUIDs

Take care of rf- and magnetic shielding!

LHe can

Thermal super-insulation

Inner vessel

Probe stick

Cryoperm Pb

Shielding
Measurements

Characterization of SQUIDs

PCB chip carrier
SQUID chip
Bonding wires

20 mm
Measurements
How to handle SQUIDs

Avoid electrostatic discharges (ESD)!
(In particular if the SQUID input coil is connected!)

Always use ESD shoes and an ESD chair.

Use ESD bracelets and connect yourself with the mat and the soldering iron.

Connect the ground of your dip stick with the experimental setup.
Measurements

Damages caused by ESD

PTB SQUID susceptometer

Repair with FIB

Anna Repolles, Javier Sese
University Zaragoza
Application examples of SQUID current sensors
Read-out of TES X-ray detectors

- **TES Xray microcalorimeters at NASA/GSFC**
- **SSA chip directly mounted on Cu block close to TESs**
- **6keV pulse → ΔΦ_{SQ} = 1.3 Φ_0**
Read-out of TES IR photon counter

TES from NIST

Operation in cryogen free 3He/4He system
Read-out of superconducting single photon detectors

cooperation with German Space Research Organisation and University Karlsruhe

NbN, 88nm linewidth, 5.5 nm thickness

SQUID Chip
Detektor Chip
SQUID NMR and low-field SQUID NMR

- Ultralow field down to 4 Hz (93 nT)
- Small room-temperature sample of volume 0.14 ml
- Broadband input coupling scheme and direct readout
- 2stage SQUID with $\epsilon_c = 50 \ h \rightarrow \text{S/N} \sim 5$ in single shot

NMR signals (FID) from oil/water mixtures in a 4:1 mass ratio at 300 K (black) and 275 K (grey).
2 samples of distilled water

304 SQUID-Sensor

$B_{Detection} \ 1.5 \ \mu T$

$B_{Polarization} \ 250 \ \mu T$

Trahms, Burghoff, Hartwig (PTB) 3 seconds
Read-out of nanoSQUIDs

He-probe stick for nanoSQUID measurement
Read-out of nanoSQUIDs

Collaboration with L. Hao, J. Gallop, O. Kazakova,

- NanoSQUID read-out with SQUID array current sensor
- Working point adjustment with auxiliary coil
- Nanoparticle excitation with exitation coil
Characterization of nanoSQUID

Collaboration with Gallop, Kazakova, Hao

SQUID loop ≈ 200 nm

$T = 6.8 \text{ K}, I = 60 \mu A$

$7.6 \text{ mT}$

Read-out of nanoSQUIDs

$\sqrt{S_\phi} (\mu \Phi_0 / \sqrt{\text{Hz}}) f (\text{Hz})$

$18.8 \mu A$

$0.2 \mu \Phi_0 / \sqrt{\text{Hz}}$
Read-out of nanoSQUIDs

NanoSQUID with magnetic nanoparticle

Bare SQUID

With particle
SQUID noise thermometers

Nyquist Formula: \( \langle U^2 \rangle = 4k_B T R \Delta f \)

Integrated current sensing noise thermometer

Magnetic field fluctuation thermometer

Chip with SQUID current sensor and noise resistor

3x3 mm² SQUID gradiometer chip
SQUID noise thermometers have to be calibrated at one reference temperature only.

\[ T = T_{\text{Ref}} \frac{S_{\Phi}(f_p, T_{\text{Ref}})}{S_{\Phi}(f_p, T_{\text{Meas}})} \]

with \( f_p \) plateau frequency.
SQUID noise thermometers

MFFT mounted in cryogen-free $^3$He/$^4$He- dilution refrigerator
Geophysical sounding

Air borne SQUID system with highly balanced SQUID gradiometers

Supracon AG, Wildenbruchstr. 15, 07745 Jena Germany, www.supracon.com
Nondestructive evaluation of materials

Commercial LT SQUID NDE system (eddy current testing) for defect inspection of materials

Michael Mück, ez SQUID Mess- und Analysesysteme, Herborner Str. 9,
Biomagnetism

Fetal magnetocardiography

304 channel system

Mother: heart breathing

child
Biomagnetism
SQUID Magnetoencephalography

Brain response

Stimulus

Loudspeaker for acoustic stimulation
Auditory Evoked Field

Signal processing & Source localization

MEG signals

Coregistration on the anatomical image

Number of averaging = 100,
2008, Feb. 4, 15:30
Goal: Combine MEG with If-MRI

1. step: If MRI imaging of the brain
Goal: Combine MEG with ULF-MRI

Whole-head system at LANL for MEG & ULF-MRI

- **Modified NeuroMag 122 for MEG and ULF-MRI**
  - 1<sup>st</sup> step: 16 clusters (MRI channels), 64 magnetometers
  - 2<sup>nd</sup> step: 61 clusters (MRI channels), 244 magnetometers
  - 15-24 reference channels
- **LN<sub>2</sub> cooled B<sub>p</sub> coils designed for up to 0.2 T**

P. Magnelind, EUCAS 2011,
Idea:
Monitor brain activity of a person with room temperature SQUIDs while he is doing strange things...

Than transmit the recorded data to the brain of another person...
Summary

Variety of SQUIDs are available for practical use at very low temperatures
→ low noise, high dynamic performance
→ easy to use and robust
→ input inductance range 1 nH ... 2 µH
→ noise thermometers available for temperature range 10 mK ... 6 K
→ operation with commercialised electronics (see www.magnicon.com)

If you are interested in using PTB SQUIDs you are welcome to discuss your application with us